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SPITZER OBSERVATIONS OF THE NEW LUMINOUS RED NOVA M85 OT2006-1

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ABSTRACT

M85 OT2006-1 is the latest and most brilliant addition to the small group of known luminous red novae (LRNe). An identifying characteristic of the previously detected events (M31 RV, V4332 Sgr, and V838 Mon) was a spectral redward evolution connected with an emerging infrared component following the optical decay. Here we report on the discovery of a similar feature in Keck NIRC and *Spitzer* photometry of M85 OT2006-1 6 months posteruption. We find that its 2.1–22 μm spectral energy distribution is best described by a blackbody with effective temperature $T_{\rm eff} = 950 \pm 150$ K and bolometric luminosity $L = 2.9^{+0.4}_{-0.5} \times 10^5\ L_{\odot}$. Assuming spherical geometry, the blackbody effective radius, $R = 2.0^{+0.6}_{-0.4} \times 10^4\ R_{\odot}$, and corresponding expansion velocity, $v = 870^{+260}_{-180}$ km s^{-1}, are remarkably similar to the properties of M31 RV 70 days after its eruption. Furthermore, we propose a search strategy for LRNe in the local universe making use of the longevity of their infrared excess emission and discuss the expected number of events in the *Spitzer* Infrared Nearby Galaxies Survey.

Subject headings: stars: individual (M31 RV, M85OT 2006-1, V838 Mon) — stars: variables: other

Online material: color figure

1. INTRODUCTION

M85 OT2006-1 was discovered by the Lick Observatory Supernova Search on 2006 January 7. It appeared as a new transient projected in the outskirts of the lenticular Virgo Cluster galaxy M85. The outburst, as observed in the optical, exhibited a plateau with a duration of about 2 months and reached an absolute peak magnitude of $M_V \cong -13$ (Kulkarni et al. 2006). Spectroscopic observations indicated that this was neither a classical nova nor a subluminous supernova. Instead, its early-time spectrum was consistent with a blackbody of $T_{\rm eff} \sim 4600$ with narrow Hα and Hβ emission. Following the plateau-phase, the optical brightness decreased rapidly and the peak emission evolved toward longer wavelengths.

A similar evolution has been observed in three other transients so far; M31 RV in Andromeda (Rich et al. 1989) and probably V4332 Sgr (Martini et al. 1999) and the extensively studied V838 Mon (Brown et al. 2002; Munari et al. 2002c; Kimeswenger et al. 2002; Bond et al. 2003; Evans et al. 2003) in the Milky Way. Among this small group, M85 OT2006-1 stands out as the most distant and brightest event approaching a bolometric peak luminosity of about $5 \times 10^6\ L_{\odot}$.

While the peak luminosities of the four sources differ, their overall observed properties are indicative of a common eruption mechanism. Thus, they were suggested to be the first members of an emerging class of eruptive transients that were recently dubbed "luminous red novae" (LRNe; Kulkarni et al. 2006).[3] The cause of the peculiar outbursts still needs to be fully established, although various explanations were proposed. The most favorable scenarios appear to be a stellar merger event in a binary system with small secondary-to-primary mass ratio (Soker & Tylenda 2003, 2006) or a planetary capture (Retter & Marom 2003).

One of the most remarkable features of M31 RV and V838 Mon was a strong infrared excess that developed a few months after the eruption (Mould et al. 1990; Lynch et al. 2004).[4] This excess emission is commonly associated with condensation of newly formed dust in the expelled envelope around the progenitor star. In this paper we present the results of a near and mid-infrared search for a similar component in M85 OT2006-1.

2. OBSERVATIONS

We observed M85 OT2006-1 using the *Spitzer Space Telescope* Infrared Array Camera (IRAC; Fazio et al. 2004) at 3.6, 4.5, 5.8, and 8 μm and the peak-up imaging mode of the Infrared Spectrograph (IRS; Houck et al. 2004) at 15.8 and 22 μm in July 2006. See Table 1 for a summary of observations. Standard pipeline post–Basic Calibrated Data products were obtained from the *Spitzer* archive.

A color-composite of the 3.6, 5.8, and 8 μm emission is shown in Figure 1 (*left*). Prior to undertaking photometry we subtracted the local host galaxy emission estimated using the IRAF task `mkskycor` (Fig. 1, *right*). The flux densities are measured through 1.9″ and 3.6″ apertures for IRAC and IRS, respectively. Aperture corrections were applied according to documented values.[5] See Table 1 for a summary of flux densities and apparent magnitudes.

In addition, we obtained simultaneous *K*-band imaging with the Keck Observatory Near Infrared Camera (NIRC; Matthews & Soifer 1994) under excellent (FWHM = 0.4″) conditions. The data were reduced using the near-infrared processing package IRtools for IRAF (D. Thompson 2006, private communication). The host galaxy emission was subtracted as described above and the flux calibration was derived using observations of the standard star SJ 9145 Persson et al. (1998). The flux measurement was obtained using a circular aperture of 0.8″ radius.

3. RESULTS

3.1. *K-band Light Curve*

In Figure 2 we show the *K*-band light curve combining the photometry from Kulkarni et al. (2006) with the NIRC observation

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[3] The terms "luminous red variables" (Bryan & Royer 1992), "stars erupting into cool supergiants" (SECS) (Munari et al. 2002b), and "mergebursts" (Soker & Tylenda 2006) were suggested as well.

[4] No infrared observations were obtained for V4332 Sgr within the first 4 yr. It is thus unconstrained whether it showed a similar evolution or not.

[5] IRAC: http://swire.ipac.caltech.edu/swire/astronomers/publications/SWIRE2_doc_083105.pdf; IRS: http://ssc.spitzer.caltech.edu/irs/pu_fluxcal.txt.

TABLE 1

Log of Observations

Start UTC	Instrument	Filter (μm)	Exposure (s)	Flux Density (μJy)	Brightness (Vega Magnitude)
2006 July 6.28	Keck NIRC	2.1	1200	13 ± 1	19.3 ± 0.1
2006 July 7.06	*Spitzer* IRAC	3.6	3000	35 ± 6	17.2 ± 0.1
2006 July 7.06	*Spitzer* IRAC	4.5	3000	40 ± 5	16.6 ± 0.1
2006 July 7.06	*Spitzer* IRAC	5.8	3000	46 ± 6	16.0 ± 0.1
2006 July 7.06	*Spitzer* IRAC	8.0	3000	40 ± 5	15.5 ± 0.1
2006 July 2.12	*Spitzer* IRS	15.6	3000	20 ± 7	$14.9^{+0.5}_{-0.3}$
2006 July 2.12	*Spitzer* IRS	22.0	3000	25 ± 20	$14.0^{+1.8}_{-0.7}$

presented here. The sparse data are consistent with a linear decay at a rate of ~0.02 mag per day followed by a flattening at about 120–180 days.

3.2. *Spectral Energy Distribution*

The 2.1–22 μm photometry at ~180 days is consistent with a blackbody with effective temperature, $T_{\rm eff} = 1030 \pm 50$ K (χ^2/dof = 3.3/5; Fig. 3, *solid line*). A fit to the IRAC and IRS data alone suggests a slightly lower temperature, $T_{\rm eff} = 900^{+140}_{-100}$ K (χ^2/dof = 0.9/4; Fig. 3, *dashed line*) and an additional, hotter component leading to a flux surplus at 2.1 μm. For the following discussion we will assume a blackbody temperature of $T_{\rm eff} = 950 \pm 150$ K for the infrared excess emission.

The bolometric luminosity after 180 days (as traced by $\sigma T_{\rm eff}^4$) was $L = 2.9^{+0.4}_{-0.5} \times 10^5\ L_\odot$ (see Table 2). The corresponding blackbody radius was $R = [L/(4\pi\sigma_B T_{\rm eff}^4)]^{1/2} = 2.0^{+0.6}_{-0.4} \times 10^4\ R_\odot$. Using 2006 January 7 as the onset of the eruption, we estimate a mean expansion velocity of 870^{+260}_{-180} km s^{-1}. The total emitted radiation energy is ~10^{47} ergs, dominated by the optical plateau during the first 3 months.

4. DISCUSSION AND CONCLUSION

We have presented the discovery of a strong 3.6–22 μm excess in M85 OT2006-1 at ~180 days. This thermal infrared component suggests dust condensation in the matter expelled during the eruption, similar to M31 RV (Mould et al. 1990) and V838 Mon (Kimeswenger et al. 2002; Lynch et al. 2004).

The derived photospheric properties of M85 OT2006-1 are resembled closest by those of M31 RV. For the latter a 1000 K dust shell with a radius of ~8000 $R_\odot$ was reported after 70 days (Mould et al. 1990; see Table 2 for a comparison). Similar to M85 OT2006-1, M31 RV showed a nearly perfect blackbody component with only a faint excess at shorter wavelengths. Also, V838 Mon displayed a single-component blackbody emission during the first 120 days (see Tylenda 2005). At this time it's effective temperature, $T_{\rm eff} = 3000$ K, and radius, $R_{\rm eff} = 2500\ R_\odot$, differed significantly from those of M85 OT2006-1 and M31 RV, although. However, V838 Mon was initially hotter ($T_{\rm eff} \sim 7000$ K) and exhibited at least two eruption phases (Munari et al. 2002c). Furthermore it resides possibly in a binary with a bright B3 V star (Munari et al. 2002a), making the interpretation of the observed quantities difficult.

Assuming a spherical geometry for M85 OT2006-1, we inferred a mean expansion velocity of ~900 km s^{-1} in 2006 June. This value is surprisingly similar to the one derived for M31 RV at comparable $T_{\rm eff}$ (~920 km s^{-1}; see Table 2). However, 900 km s^{-1} in M85 OT2006-1 is significantly larger than the velocity obtained from the Hα line width in February 2006 (350 ± 140 km s^{-1};

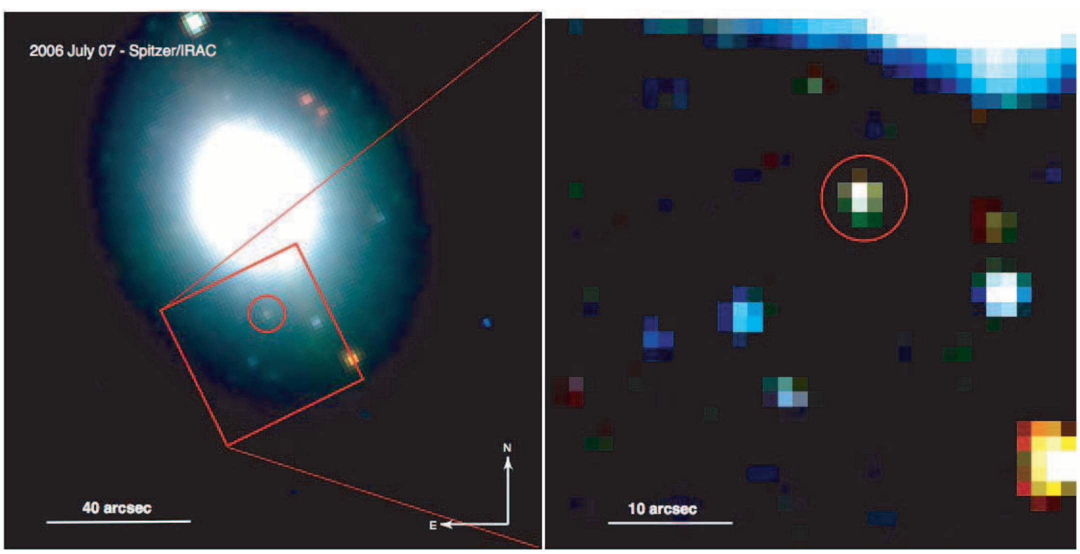

Fig. 1.—*Left:* IRAC color-composite image of M85 using 3.6, 5.8, and 8 μm photometry obtained ~6 months after the eruption. The position of M85 OT2006-1 is indicated by the circle. *Right:* Zoom into the location of the transient after subtraction of the galaxy light.

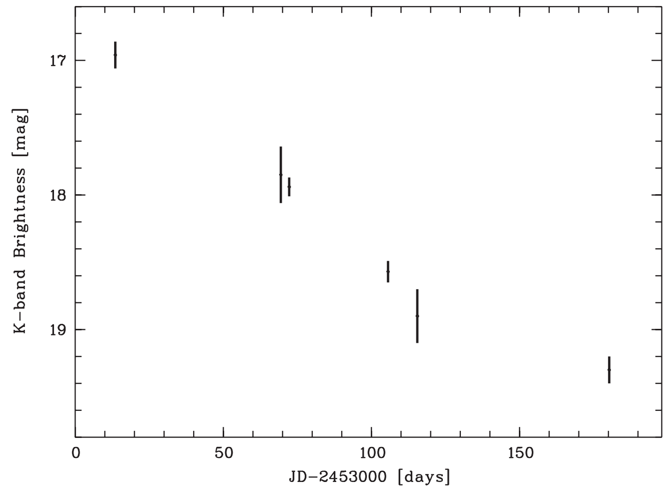

FIG. 2.—*K*-band light curve; $t = 0$ corresponds to the discovery date, 2006 January 7. Data at $t < 120$ days were reported in Kulkarni et al. (2006). The early-time light curve can be approximated by a linear decay with a slope of $\sim$0.02 mag per day. The late-time NIRC photometry suggests a significant flattening between 120 and 180 days.

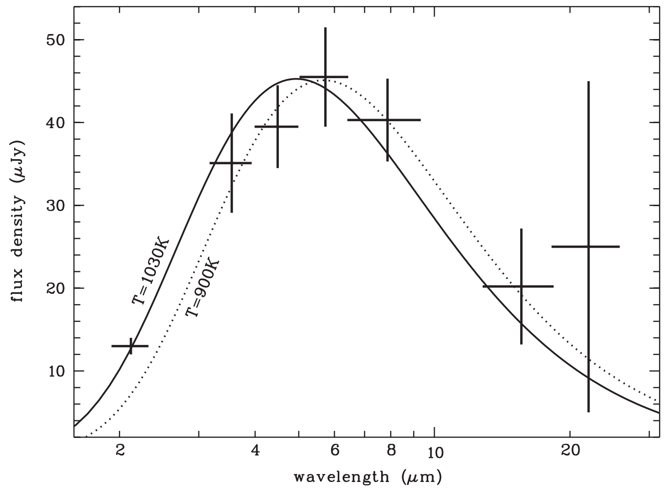

FIG. 3.—Near and mid-infrared flux densities observed in 2006 July (*crosses*). The solid line shows a blackbody with $T_{\rm eff} = 1030$ K fitted to 2.1–22 μm photometry. Omitting the *K*-band suggests a lower $T_{\rm eff}$ (900 K; *dashed line*) and an additional hotter component.

Kulkarni et al. 2006). A solution to this apparent discrepancy lies in the source geometry. In case of an aspherical expansion, e.g., an oblate geometry observed face-on, the velocity ($\propto$blackbody radius), may be overestimated. Alternatively, the large velocity inferred from the infrared observations, can be caused by radiative acceleration as a result of a long-lasting engine activity or multiple phases of energy injection into the expanding material. Furthermore, the Balmer emission may have originated in a low-velocity region unrelated to the matter that produced the late-time blackbody component.

In V838 Mon the shell became partly transparent after $\sim$120 days. Furthermore, the temperature slowly increased again after $\sim$250 days, possibly as the result of a gravitationally induced collapse of the inflated envelope (Tylenda 2005). A similar behavior was also reported for V4332 Sgr about 9 yr after its eruption (Tylenda et al. 2005). Whether or not M85 OT2006-1 will evolve alike needs to be addressed with future infrared observations.

Most of our knowledge on LRNe prior to our analysis was based on detailed studies of a single event, V838 Mon. Here we have shown that variations in the infrared evolution exists among the small sample of sources. Whether the cause of these variations lies in the progenitor, environment or some other unnamed parameter remains to be solved. Indeed, already the underlying stellar populations are not uniform. While V838 Mon resides within a B star cluster (Afşar & Bond 2007), M85 OT2006-1 (Kulkarni et al. 2006), M31 RV (Rich et al. 1989), and V4332 Sgr (Tylenda et al. 2005) probably originated from low-mass stars. However, it is clearly premature to speculate on a possible bimodality here.

The next step forward requires a significant increase of the LRNe sample. Estimates based on the few known events suggest rates of approximately a dozen per year out to a distance of 20 Mpc (Kulkarni et al. 2006). Similar predictions come from the theory of violent mergers of both massive and low-mass stars (Soker & Tylenda 2006). Thus, a dedicated search for LRNe is expected to net a substantial number of new events and may revolutionize our understanding of these elusive transients.

A promising strategy to detect new LRNe similar to M85 OT2006-1 and M31 RV is to make use of their characteristic infrared emission properties. The IRAC colors of a 900–1000 K blackbody can easily be discriminated from the majority of known stellar objects, AGNs and unresolved galaxies (Fig. 4, *left*). Only early-type T dwarfs (T2–T4; Patten et al. 2006), which have similar $T_{\rm eff}$, exhibit comparable 3.6–8 μm colors. However, the latter can be identified by their strong molecular absorption bands in the near-infrared (e.g., CH_4, H_20; for a recent review see Kirkpatrick 2005), which also lead to significant deviations from a perfect blackbody spectrum (offset from blackbody line in Fig. 4).[6]

The main advantage of searching in the infrared is that the detection probability is increased with respect to optical searches by the ratio of infrared-bright time (a few years) to optical plateau duration (a few months). Using the predictions of Soker & Tylenda (2006) of approximately one LRN per galaxy every 10–50 yr, we can estimate the number of anticipated events in an existing sample like the *Spitzer* Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003). SINGS comprises IRAC observations of 75 galaxies within 30 Mpc (mean distance 9.5 Mpc) with sensitivities similar to the observations presented here. We predict that a search in the archival data using the described color criterion might lead to the detection of as much as 1–10 new LRN events. A similar number of events could be found in a large survey of nearby galaxies using the deep imaging mode of *Akari* (previously known as *ASTRO-F*; Matsuhara et al. 2005).

We close the paper by emphasizing that the search for stellar mergers can be expected to have a substantial impact over the next years. Similar to the history of the field of gamma-ray bursts, a large increase of well-studied events is anticipated to lead to exciting new insights into this emerging family of enigmatic transients.

[6] We note that V838 Mon revealed strong absorption bands (e.g., H_2O, CO, OH, and SH; Lynch et al. 2004) after $\sim$1 yr together with a hot continuum ($T_{\rm eff} \sim 2700$ K) inconsistent with a simple blackbody. Thus, it would have been difficult to identify by its infrared colors alone. Whether this is caused by intrinsic or environmental differences with respect to M85 OT2006-1 and M31 RV or only the result of a slower evolution is unconstrained.

TABLE 2

INFERRED BLACKBODY PARAMETERS

Source	L_{peak} ($\times 10^5\ L_\odot$)	$T_{eff,peak}$ ($\times 10^3$ K)	R_{peak} ($\times 10^3\ R_\odot$)	L_{late}[a] ($\times 10^5$ L$_\odot$)	$T_{eff,late}$ ($\times 10^3$ K)	R_{late} ($\times 10^3\ R_\odot$)	R_{late}/t (km s^{-1})
M85 OT2006-1[b]	$\sim$50	$\sim$4.6	$\sim$3.6	$2.9^{+0.4}_{-0.5}$	0.95 ± 0.15	20^{+6}_{-4}	870^{+260}_{-180}
M31 RV[c]	$\sim$8	$\sim$4	$\sim$2	$\sim$0.6	$\sim$1	$\sim$8	$\sim$920

[a] At $t \sim 180$ days for M85 OT2006-1 and $t \sim 70$ days for M31 RV.
[b] Peak values are from Kulkarni et al. (2006), and late-time values are from this paper.
[c] The peak luminosity is from Rich et al. (1989), and the remaining values are from Mould et al. (1990).

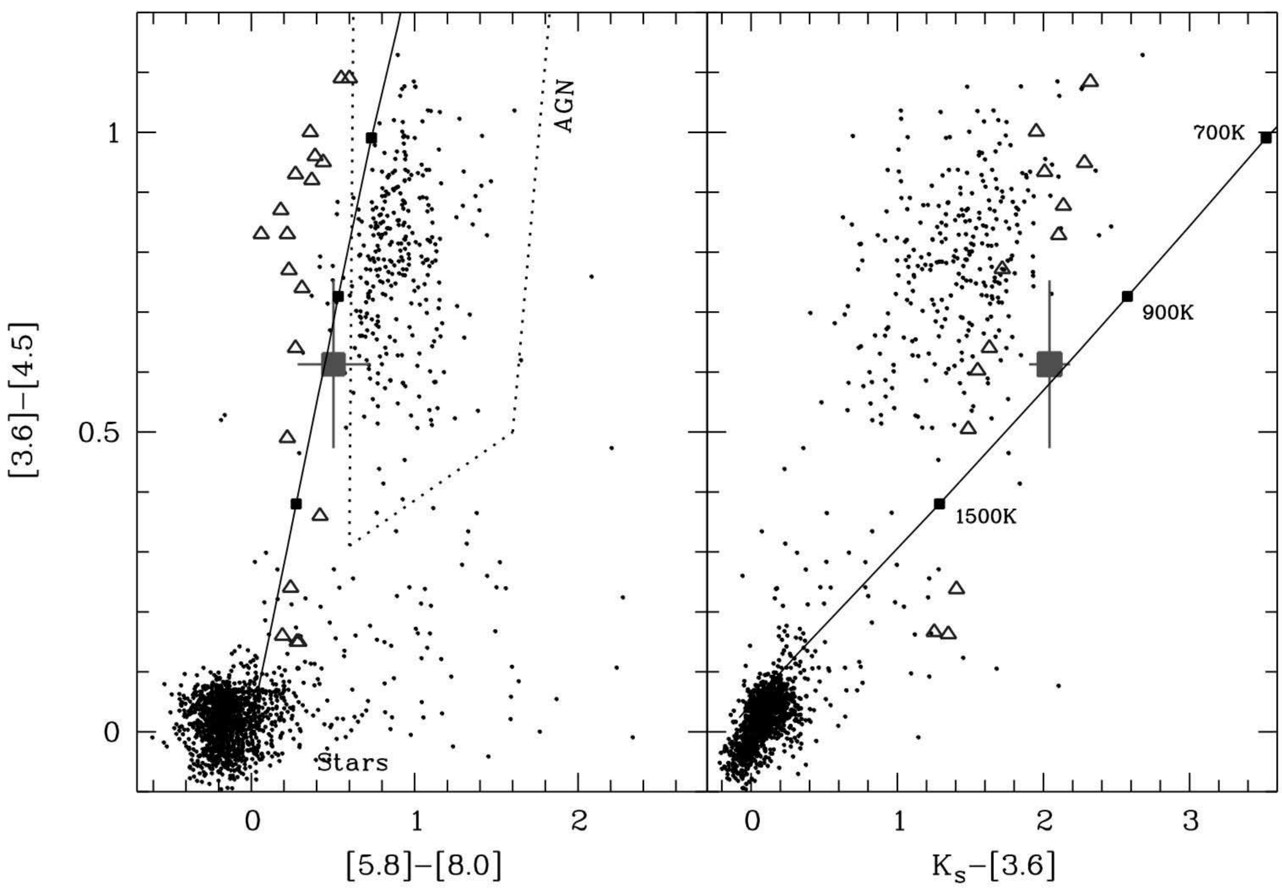

FIG. 4.—*Left:* Color-color diagram of [3.6] − [4.5] vs. [5.8] − [8] for M85 OT2006-1 (*square*), pointlike sources in the S-COSMOS field (*dots*; Sanders et al. 2007, courtesy of the S-COSMOS team) and T dwarfs (*triangles*; Patten et al. 2006). The locations of stars and AGNs (contours from Stern et al. 2005) are indicated. Unresolved galaxies constitute the distribution of sources with [5.8] − [8] > 1 mag and [3.6] − [4.5] < 0.5 mag. Only T dwarfs have similar colors as M85 OT2006-1 after ~180 days. blackbody colors follow the solid line. *Right:* Same for [3.6] − [4.5] vs. K_s − [3.6]. Strong near-infrared absorption bands in T dwarfs lead to a larger discrepancy compared to a pure blackbody spectral shape. [*See the electronic edition of the Journal for a color version of this figure.*]

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